Investigation of Unequal Planar Wireless Electricity Device for Efficient Wireless Power Transfer

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Abstract. *This article focuses on the design and investigation of a pair of unequally sized wireless electricity (Witricity) devices that are equipped with integrated planar coil strips. The proposed pair of devices consists of two different square-shaped resonator sizes of 120 mm × 120 mm and 80 mm × 80 mm, acting as a transmitter and receiver, respectively. The devices are designed, simulated and optimized using the CST Microwave Studio software prior to being fabricated and verified using a vector network analyzer (VNA). The surface current results of the coupled devices indicate a good current density at 10 mm to 30 mm distance range. This good current density demonstrates that the coupled devices' surface has more electric current per unit area, which leads to a good performance up to 30 mm range. Hence, the results also reveal good coupling efficiency between the coupled devices, which is approximately 54.5 % at up to a 30 mm distance, with both devices axially aligned. In addition, a coupling efficiency of 50 % is achieved when a maximum lateral misalignment (LM) of 10 mm, and a varied angular misalignment (AM) from 0° to 40° are implemented to the proposed device.*

Keywords

Coupling efficiency, magnetic resonance coupling, misalignment, wireless power transfer, Witricity

1. Introduction

Wireless power transfer (WPT) has been a subject of interest among researchers since the feasibility of transmitting power wirelessly was reported by Nikolai Tesla in 1900 [1], [2]. This research interest is further stimulated by the evolution of wireless technologies from fourth generation (4G) to fifth generation (5G) technologies, expected to become mainstream in the year 2020. Compared to 4G, 5G technologies are more focused on the device-to-device communication (D2D) and wearable devices [3]. To facilitate wearable devices, various designs of WPT systems have been introduced through the use of such methods as strong magnetic resonance coupling, also known as Wireless Electricity (Witricity) [4], [5], conventional inductive and capacitive coupling [6], [7] and rectifying antennas (rectennas) [8]. The strong magnetic resonance technique uses two coupled magnetized objects within a non-radiative near-field region at megahertz (MHz) frequencies. As reported in [4], the most efficient way to realize this technique is to couple two identical designs on a similarly resonant frequency. The majority of commercial modern gadgets, including smart phones, tablets, notebooks, and pacemakers, possess the capacity to utilize Witricity. These devices are usually designed to be compact in size. While Witricity transmitter sizes are typically not critically constrained, it is crucial for the Witricity receiver to be as compact as possible in order to be placed in the intended device to be powered. However, there is a drawback when designing a compact Witricity device. The range of transferred power firstly depends on Witricity size, which corresponds to the wavelength. Thus, smaller Witricity device tends to transfer less efficient power compared to larger Witricity device. Therefore, the feasibility of coupling unequally sized transmitter and receiver Witricity devices is shown in this article. Nevertheless, the level of transferred power is not limited by the size of the device, but also influenced by the transfer distance and alignment of the transmitter and receiver as presented investigation.

In a bid to achieve compact designs, planar-type Witricity devices have been proposed in [9–12]. These designs use flat single or multilayer coils, with different conductor levies, to create a homogenous magnetic field between transmitter and receiver [9]. In [10], the authors have proposed a Witricity design with equal transmitter and receiver (162 × 162 mm^2) sizes by using a plastic lamella board, and investigate the performance of the Witricity devices when angular and lateral misalignments occur. Copper tape is used as the inductor coil and capacitor plates. For the single coil, copper wire has been attached to the capacitor plates. This single coil provides high inductance due to its loop's large diameter and thick cross-sectional area. Another Witricity design has been proposed in [11], which is a quarter of the size (80 × 80 mm^2) of the design reported in [10]. Double-sided copper coated FR-4 substrate has been used in this more compact Witricity device design, thereby eliminating the need for thick copper wire. Similar to the designs proposed in [10] and [11], an equal-sized transmitter and receiver design has been proposed in [12]. The design, which is stated to be more compact in size (40×40 mm^2), however, replaces the cheaper FR-4 substrate with a high performance and pricy Rogers RO3010 substrate.

Thus, to overcome the problem of the high cost of the Rogers RO3010 substrate, this work proposes the coupling of two with unequal-sized Witricity devices. The proposed arrangement uses a smaller receiver device, and provides a comparable performance to a larger design proposed in [10], yet utilizing low cost Flame Retardant 4 (FR-4) as the substrate. Furthermore, given the small form factor requirements of modern gadgets, the proposed design of the Witricity device has an integrated planar coil in the resonant unequal-sized transmitter and receiver. This article also investigates the impact of misalignments between the coupled unequal-sized Witricity devices.

2. Design of Witricity Devices

In this article, a larger Witricity device is proposed to function as a transmitter, while a smaller one functions as a receiver. A larger-sized transmitter is needed to maximize the transferable energy distance, as the distance is always proportional to its coil size. The reduction of transmitter size will lead to the reduction of maximum transferable energy distance. The receiver is purposely designed to have smaller dimension compared to the transmitter in order to suit today's modern devices, which typically compact in size. Figure 1 depicts a transmission scheme from the first port to the second port, while Figure 2 shows the arrangement of the proposed Witricity device in three-dimensional (3D) simulation tool of CST Microwave Design Studio, as well as its fabricated prototype.

In Fig. 1 and 2, each transmitter and receiver that consists of two conducting layers: top and bottom are separated by the air gap. The top layer consists of a rectangular spiral coil inductor (Tx and Rx coil), while the bottom layer has four capacitor plates that are diagonally structured and attached to a single turn coil (Tx and Rx loop). The chosen Flame Retardant 4 (FR-4) substrate, with a relative permittivity of 4.41, loss tangent of 0.025, 1.6 mm thickness, and 35 µm thickness of copper coating, is sandwiched between these two conducting layers.

Both transmitter and receiver need to be operated on a similar operating frequency to allow the strongly coupled magnetic resonance technique to function properly. Based on [11], the parameters such as dimension of capacitor plate and the number of turns of spiral coil can be tuned for the device to operate at a specific frequency. A larger design, which commonly tends to have a lower frequency, can operate at a higher resonance frequency by tuning the above-mentioned parameters. The operating resonance fre-

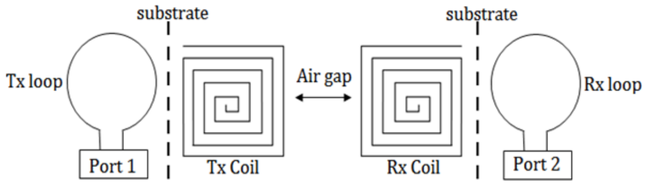
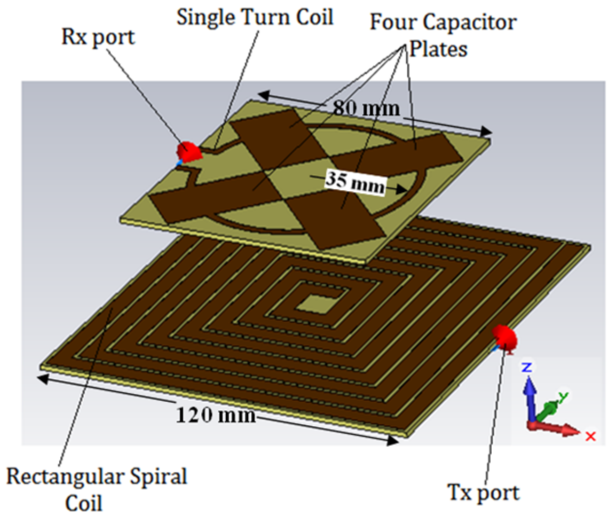
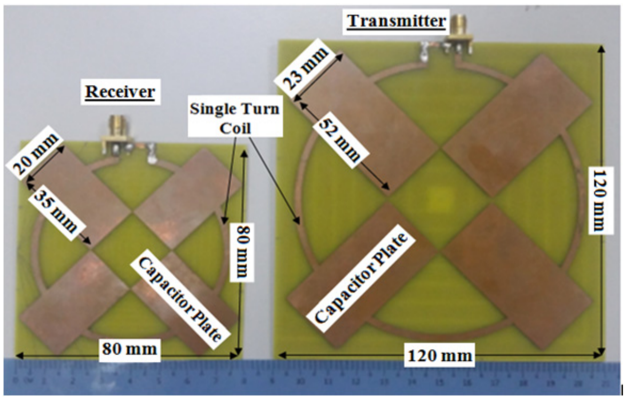


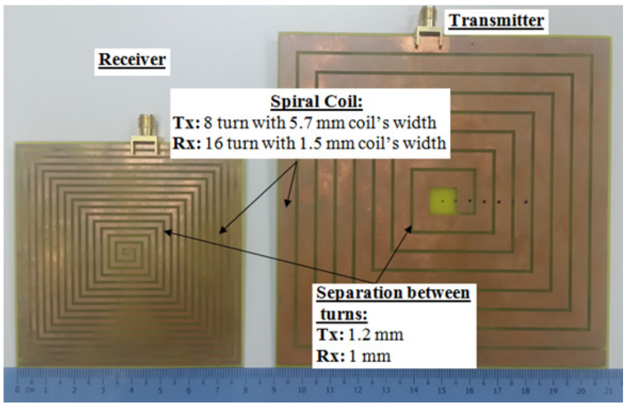
Fig. 1. Witricity device transmission scheme.



(a)



(b)



(c)

Fig. 2. The unequally sized Witricity device design: (a) the generated 3D layout in CST Microwave Design Studio, (b) the bottom view, and (c) the top view of the fabricated prototype.

quency denoted by f_r [11], strongly depends on the capacitance C and the inductance L value, which is described in (1). C depends on the dimensions of the capacitor plates and the thickness of the substrate, and L relies on the spiral coils, which consequently influence the device's induction strength. In addition, the capacitor plates store energy from the single turn coil prior to the transferal of energy to the spiral coils located at the top layer of the device.

$$f_r = \frac{1}{2\pi\sqrt{LC}}. \quad (1)$$

The transmitter and receiver are designed to resonate at a similar frequency according to the dimensions summarized in Tab. 1. The individual and decoupled transmitter and receiver are set to resonate around 18–20 MHz. These two unequally sized resonators are then aligned horizontally or vertically to perform at optimal condition. The optimal condition can be achieved without lateral and angular misalignment. It is expected that the coupling resonance frequency will shift to a higher band when the transmitter and receiver are coupled. In addition, this coupling resonance frequency is also expected to shift depending on the air gap separation distance, which in this design is from 10 mm to 40 mm. The performance of the device is studied by varying the air gap distances from 10 mm to 40 mm. Subsequently, the device's coupling efficiency is evaluated and analyzed for cases of lateral and angular misalignment.

Parameter	Transmitter	Receiver
Size	120 mm × 120 mm	80 mm × 80 mm
Number of turns of spiral coil	8	16
Width of spiral coil	5.7 mm	1.5 mm
Capacitor plate	52 mm × 23 mm	35 mm × 20 mm
Inner radius of single turn coil	43 mm	35 mm
Width of single turn coil	2.5 mm	2.5 mm

Tab. 1. The summarized dimensions of the proposed Witricity device.

3. Results and Discussion

The results discussed in this article are divided into three sub-sections: surface current, S-parameters, and misalignment. The concerned measurement setup of the proposed Witricity device is shown in Fig. 3.

The surface current indicates the current density level, and the distribution of the current on the conductor's surface during the transfer process. The color sequence as shown in Fig. 4, from the highest current density to the lowest, is represented by red, yellow, green, and blue. The insertion loss, S_{21} parameter is used to analyze the efficiency of the Witricity as in (2). Equation (2) presents the efficiency of the output power at the receiver referenced to input power at the transmitter [13], [14]:

$$\eta_{21} = |S_{21}|^2 \times 100\%. \quad (2)$$

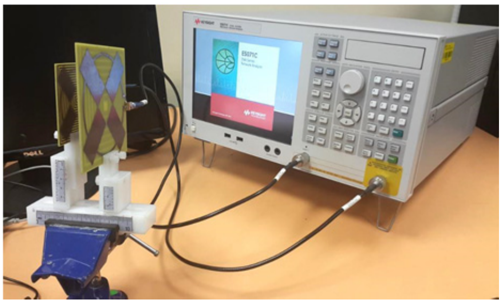


Fig. 3. The measurement setup of the proposed Witricity device.

The S_{11} and S_{22} describe the reflection coefficients at the transmitter and receiver, respectively. Lateral and angular misalignments are introduced to the device to evaluate its performance.

3.1 Surface Current

Figure 4 shows the current distribution on the conductive surface of the Witricity device over a 10 mm to 40 mm air gap distance. The surface current density, $\tilde{\mathbf{J}}_s$ can be expressed by (3):

$$\tilde{\mathbf{J}}_s = \hat{\mathbf{n}} \times \left(\tilde{\mathbf{H}}_2 - \tilde{\mathbf{H}}_1\right) \quad (3)$$

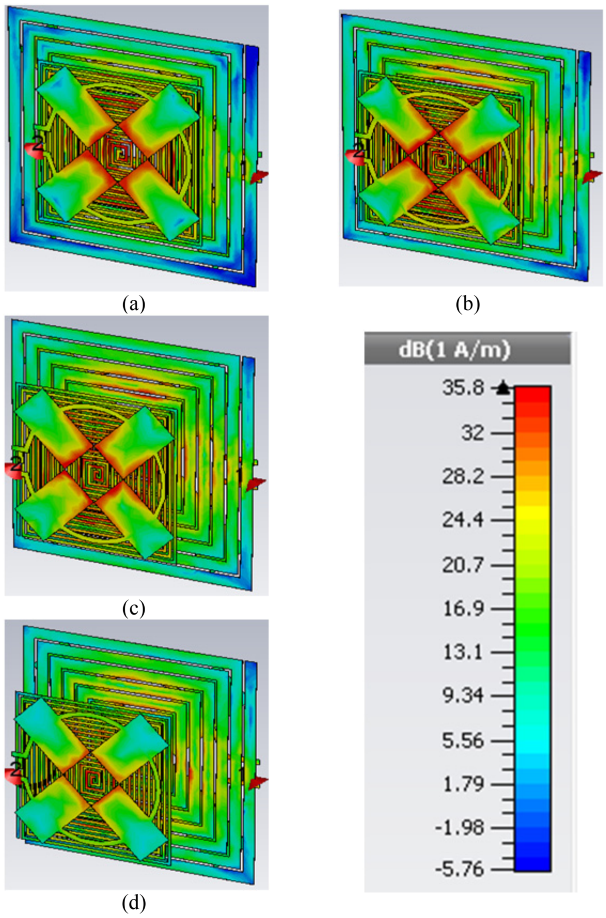


Fig. 4. The Witricity current distribution with different air gap separation distances: (a) 10 mm, (b) 20 mm, (c) 30 mm, and (d) 40 mm.

where $\hat{\mathbf{n}}$ and $\tilde{\mathbf{H}}_1$ and $\tilde{\mathbf{H}}_2$ are a normal unit vector pointing out of the medium at the interface and magnetic-field intensity in two mediums, accordingly.

The highest density of current distribution observed, which reflects the highest received power, is concentrated in the middle area of the device. Otherwise, the majority of the transmitter and receiver current densities fall within a mid-range of approximately 13 Am^{-1} to 17 Am^{-1}. Observations reveal that the receiver has a better current density resulting from higher electric current at its smaller area of cross section due to its small size, which allows for full-coverage areas of coupling from the transmitter. This better current density allows for better coupling and matching at the receiver side. A similar pattern can be noted up to 30 mm, which speaks to a good coupling efficiency. A lower current density is observed for an air gap distance of 40 mm, implying that the receiver (the smaller size resonator) tends to experience more power at distances shorter than 40 mm. The transmitted power is limited to certain transferable distances that become weaker as it travels further. It can be inferred that increasing air gap distance has reduced the effectiveness of power coupled to the receiver and the non-transferrable power will be reabsorbed by the transmitter.

3.2 Scattering Parameters

A comparison of the simulated and measured coupling effect between the transmitter and the receiver is shown in Fig. 5. The –3 dB line in Fig. 5 indicates the benchmark of 50 % coupling efficiency. The simulation result in Fig. 5 shows that the maximum transferable distance is 30 mm, with 52.2 % coupling efficiency, and an effective bandwidth between 19.5 to 20.4 MHz. This result is verified by measurement at 30 mm, with 54.5 % efficiency in the 19.5 to 20.1 MHz band. This has proved that the proposed Witricity device transfers power wirelessly at a maximum of 30 mm separation distance with more than 50 % coupling efficiency, and agrees with the surface current findings in Sec. 3.1. The operating frequency at the 40 mm air gap distance is not considered, as the coupling efficiency results are less than 50 % (approximately 31.6 %) for both the simulation and measurement. The summary of the coupling efficiency, derived from $|S_{21}|^2$ as in (2) is tabulated in Tab. 2.

The transmitter and receiver reflection coefficients when coupled together are shown in Fig. 6 and Fig. 7, respectively, with the corresponding return losses tabulated in Tab. 2. The larger positive of return loss indicates the small amount of reflected power relative to its incident power. Both simulation and measurement results of the return loss show good agreement, which complies with the 10 dB reference when the separation distance is varied up to 10 mm distance for Port 1 at the transmitter and 30 mm for Port 2 at the receiver. Figure 6 shows the magnitude of the reflection coefficient at Port 1, which is at the transmitter when both transmitter and receiver are coupled. It can be seen that S_{11} is less than –10 dB at up to a 10 mm distance in both the simulation and measurement results. Due to the different sizes of the transmitter and receiver, the signals are easily distorted and reflected back to the transmitter when the distance is more than 10 mm, which will affect the matching at Port 1 (as indicated in Fig. 6 and Tab. 2).

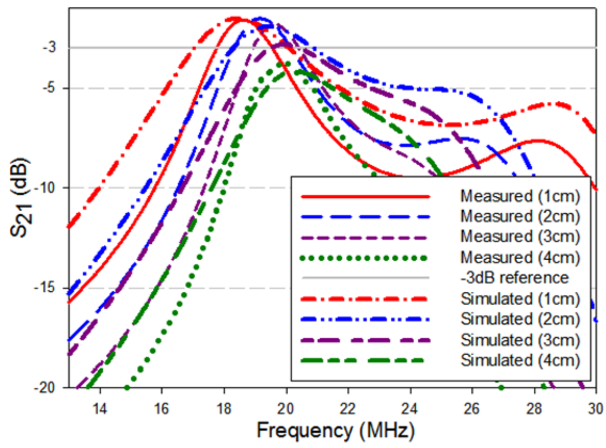


Fig. 5. Simulated and measured results of S_{21} of the unequal size of Witricity device from 10 mm to 40 mm separation distance.

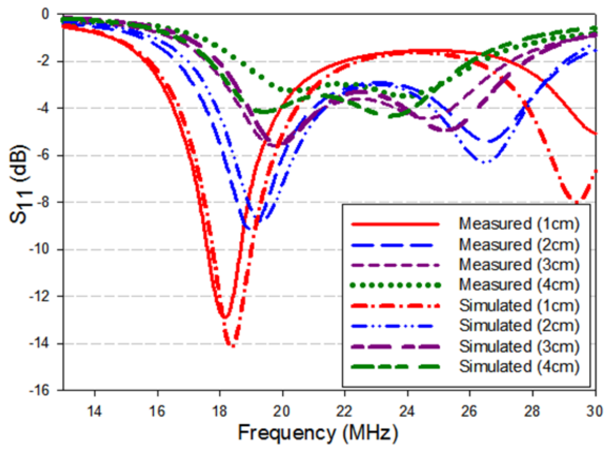


Fig. 6. Simulated and measured results of S_{11} of the unequal size of Witricity device from 10 mm to 40 mm separation distance.

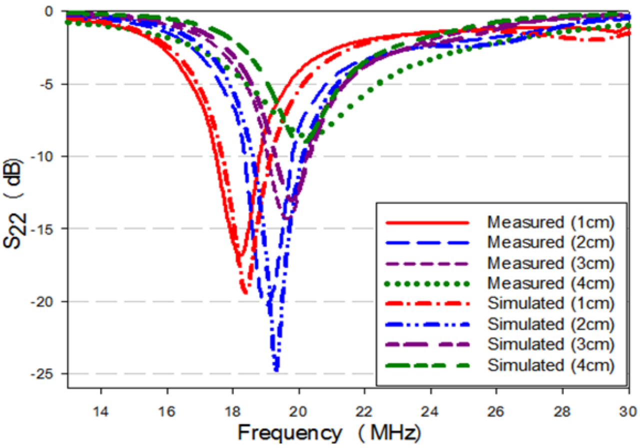


Fig. 7. Simulated and measured results of S_{22} of the unequal size of Witricity device from 10 mm to 40 mm separation distance.

Distance (mm)	Operating Frequency (MHz)		Coupling Efficiency (%)		Return Loss at Port 1 (dB)		Return Loss at Port 2 (dB)	
	S	M	S	M	S	M	S	M
10	17.1-20.0	18.1-19.6	70.3	64.1	≥ 10	≥ 10	≥ 10	≥ 10
20	18.3-20.8	19.1-20.4	64.2	62.2	≥ 8	≥ 8	≥ 10	≥ 10
30	19.5-20.4	19.5-20.1	52.2	54.5	≥ 5	≥ 5	≥ 10	≥ 10
40	-	-	31.6	31.6	≥ 3.7	≥ 3.5	≥ 8	≥ 8

*S = Simulation, M = Measurement

Tab. 2. Tabulated results of coupling efficiency and return loss at Port 1 and 2.

The return loss of the receiver side (Port 2) is shown in Tab. 2 based on its reflection coefficient magnitude (plotted in Fig. 7). It can be clearly seen that the resonance frequency increases along with the increment of separation distance, with an acceptable return loss of 10 dB up to 30 mm distance. At 40 mm, the return loss is still quite close to 10 dB, which indicates the good impedance-matching of the receiver at this distance. Both simulation and measurement results show good performance of return loss at Port 2 up to 30 mm. Hence, good coupling efficiency up to a maximum 30 mm distance is expected.

3.3 Lateral and Angular Misalignment

The condition of lateral misalignment (LM) and angular misalignment (AM) is investigated in order to observe the degree to which the performance of the Witricity devices is affected when misalignment exists during power transmission. The illustration of the Witricity devices with AM and LM is shown in Fig. 8. The investigation focuses on coupling efficiency when the devices experience LM from 5 mm to 30 mm distance and an angular misalignment ranging from 0° to 40°.

Figure 9 shows the coupling efficiency performance when the LM is varied from 0 to 30 mm without AM. A similar result of approximately 70 % coupling efficiency is observed from the devices with a 10 mm air gap for LM up to 20 mm. With this, a slight decrement of coupling efficiency is noted from the other air gap distances. With a 50 % coupling efficiency, the plotted results show the maximum acceptable LM to be 15 mm when a maximum 30 mm air gap distance is applied.

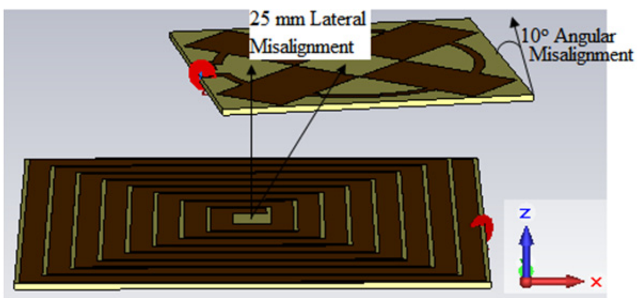


Fig. 8. Configuration of Witricity devices with 10° AM and 25 mm LM.

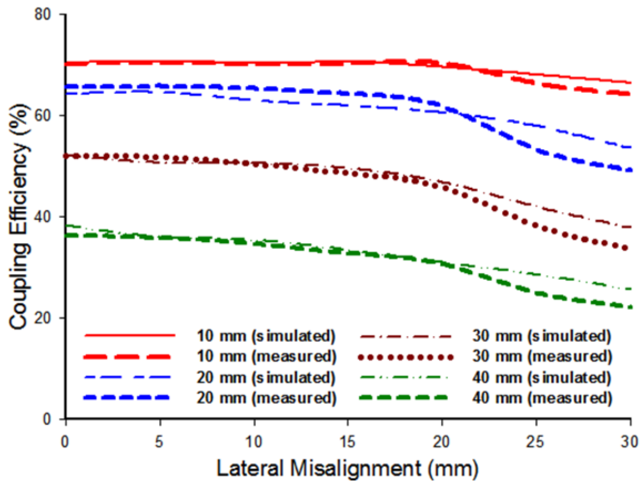


Fig. 9. The coupling efficiency performance for a 10 mm to 40 mm air gap separation distance with a 0 to 30 mm lateral misalignment (LM).

The effect of AM variation from 0° to 40° is depicted in Fig. 10. Aside from varying the AM, the figure also shows the effect of LM varying from 5 mm to 20 mm. In this investigation, the distance between transmitter and receiver is set to be at 30 mm. Shown in the figure, 50 % coupling efficiency is achievable when 0° to 40° AM variation is introduced and a maximum LM of 10 mm exists. With constant air gap separation between transmitter and receiver, as well as similar LM and 0° to 40° AM, the Witricity devices demonstrate a 1.5 % ripple size of the oscillated coupling efficiency. However, the measured results show nearly constant and less oscillating results compared to the simulation. As expected, when the transmitter and receiver do not experience any LM but only AM, the facing area between transmitter and receiver is nearly similar, which results in almost constant coupling efficiency.

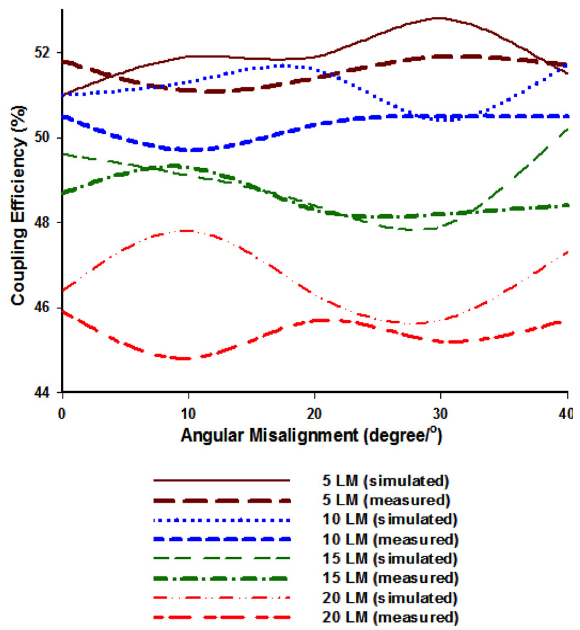


Fig. 10. The coupling efficiency performance for 10° to 40° of AM and 5 to 20 mm of LM.

Work	Transmitter Size (mm^2)	Receiver Size (mm^2)	Simulation (Distance-efficiency)	Measurement (Distance-efficiency)
[10]	162 × 162	162 × 162	Not specified	50 mm-52.3%
[11]	80 × 80	80 × 80	30 mm-52.6%	Not specified
[12]	40 × 40	40 × 40	30 mm-30.0%	30 mm-43.0%
Proposed work	120 × 120	80 × 80	30 mm-52.2%	30 mm-54.5%

Tab. 3. The size and performance comparison between the proposed and related works in [10], [11] and [12].

Table 3 summarizes a comparison of the transmitter and receiver size, transferable distance and efficiency between the proposed design and other works reported in [10], [11] and [12]. In [10], the measurement shows a good result for up to 50 mm distance. However, the size is too large to be fitted to modern devices. Therefore, more compact design has been proposed in [11] and its simulation results present a good performance for up to 30 mm distance, which is an adequate amount in wireless power transfer application. Nonetheless, no measurement has been performed in [11]. In [12], the authors proposed a smaller Witricity design compared to [11], however, the design is good for only up to 20 mm distance. Even though [12] shows a possibility of achieving a more compact design, nevertheless, the material that has been used is expensive and also the results show a decrement in the maximum transferable distance. Hence, this work proposed a fairly design size and lower cost material, which is similar to the material proposed in [11] with better and reliable measurement performance for up to 30 mm distance, 10 mm lateral misalignment and 40° angular misalignment. This work also shows that, to achieve better performance, the transmitter size can be increased as this work performs better compared to [11], which is 54.5 % measurement results compared to 52.6 % simulation results performed by [11].

4. Conclusion

In this article, the design of a pair of unequally sized Witricity devices integrated with a thin coil strip has been presented. The simulation and measurement results show that the device is coupled at a maximum air gap of 30 mm with 54.5 % efficiency. With regard to the performance of the Witricity device given lateral and angular misalignment, a maximum LM of 10 mm can be achieved with the variation of AM from 0° to 40°. The results indicate a potential for efficient wireless power transfer to devices that require more stringent receiver size restrictions.

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